DISCRETE EVENT SIMULATION OF
DISTRIBUTED TEAM COMMUNICATION

THESIS

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Presented to the Faculty
Department of Systems Engineering
Graduate School of Engineering and Management
Air Force Institute of Technology
Air University
Air Education and Training Command
in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Systems Engineering

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March 2012

AFIT/GSE/ENV/12-M07

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Abstract

As the United States Department of Defense continues to increase the number of Remotely Piloted Aircraft (RPA) operations overseas, improved Human Systems Integration becomes increasingly important. RPA systems rely heavily on distributed team communications determined by systems architecture. Two studies examine the effects of systems architecture on operator workload of US Air Force MQ-1/9 operators. The first study ascertains the effects of communication modality changes on mental workload using the Improved Research Integration Pro (IMPRINT) software tool to estimate pilot workload. This study shows that, through the proper allocation of communication between modalities, workload can be reduced. The second study uses IMPRINT to model Mission Intelligence Controllers (MICs) and the effect of the system architecture upon them. Four system configurations were simulated for four mission activity levels. Mental workload, monitoring time and the number of delayed tasks were estimated to determine the effect of changing system architecture parameters. Literature and MIC interviews provided parameters for the model. The analysis demonstrates that the proposed changes have significant effects on workload and system monitoring time.

This work is dedicated to the God of the Bible, and to my wonderful wife.

Acknowledgements

The author would like to thank the members of his committee and the operators and test personnel at Creech AFB, NV who sacrificed valuable hours to help the author with this research. The author would also like to thank his sponsor, Lt. Col Anthony Tvaryanas, for his expansive knowledge and passion for human systems integration. Also, the author would like to acknowledge his sponsor and the Department of Systems Engineering for the resources used to conduct this research.

Travis J. Pond

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DISCRETE EVENT SIMULATION OF DISTRIBUTED TEAM COMMUNICATION

I. Introduction

The U.S. Department of Defense (DoD) has been a major developer of RPA technology which it has used primarily for intelligence operations. The DoD continues to fund RPA development, even in an otherwise austere acquisitions environment (Defense, 2011). Congress has passed legislation to begin integration of civil and commercial RPAs into the national airspace system (House., 2011).

This research makes a case for including communication requirements in future system designs through two studies which examine the effects of architecture changes on communication related workload. The Improved Research Integration (IMPRINT) software tool was used to create executable communications architecture models in both studies. The models draw from the experiences of qualified MQ-1 Predator and MQ-9 Reaper operators interviewed by the author, and represent the systems they use.

MQ-1 and MQ-9 operators currently use military internet relay chat (mIRC), radio and intercom systems to communicate with co-located and distributed teams. Modalities are fixed in current operations, meaning that vocal messages are always heard and visual messages are always seen. The first study is centered around the MQ pilot and explores the ramifications of being able to shift message allocation between the auditory-verbal and visual-verbal channels. It is assumed that communication arriving on one channel could be reallocated to another channel. Reallocation could presumably occur as a result of automation or policy changes to the way users employ

communication channels within the network. This allocation change shifts the mental resource demand, which changes the workload induced by the system.

The second study examines the effects of architecture changes on workload for the mission intelligence coordinator (MIC). Changing the number of communication nodes and exclusion of secondary navigation tasks constitute potential system design changes. The current systems and design changes are modeled to determine the effects of the changes.

Effective and efficient communication is foundational to military strength and is especially important in mission areas where many of the collaborators are distributed around the globe yet must communicate in real time to complete the mission objectives. Future system requirements will need to reflect cognizance of how communications overhead and team structure can influence workload and mission performance.

II. Communication Modality Allocation

This paper was presented at the Conference of Systems Engineering Research (CSER) in St. Louis, Missouri on March 23, 2012.

Allocation of Communications to Reduce Mental Workload

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Abstract As the United States Department of Defense (DOD) continues to increase the number of Remotely Piloted Aircraft (RPA) operations overseas, improved Human Systems Integration (HSI) becomes increasingly important. Manpower limitations have motivated the investigation of Multiple Aircraft Control (MAC) configurations where a single pilot controls multiple RPAs simultaneously. Previous research has indicated that frequent, unpredictable, and oftentimes overwhelming, volumes of communication events can produce unmanageable levels of system induced workload for MAC pilots. Existing human computer interface design includes both visual information with typed responses, which conflict with numerous other visual tasks the pilot performs, and auditory information that is provided through multiple audio devices with speech response. This paper extends previous discrete event workload models of pilot activities flying multiple aircraft. Specifically, we examine statically reallocating communication modality with the goal to reduce, and minimize, the overall pilot cognitive workload. The analysis investigates the impact of various communication reallocations on predicted pilot workload, measured by the percent of time workload is over a saturation threshold.

 Selection Keywords: Workload; Multiple Resource Theory; multiple autonomous systems; Human computer interface

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2.1 Introduction

Over the past several decades, the US Air Force has harnessed and exploited the immense tactical power that middle and high-altitude Remotely Piloted Aircraft (RPAs) bring to the battlefield. As a consequence, the demand for RPA operational support continues to increase. It is important to realize that RPAs are part of a complex system. The system has many components including one or more air vehicles, ground control stations (GCS) for both primary mission control and takeoff/landing, a suite of communications (including intercom, chat, radios, phones, a satellite link, etc), support equipment, and operations and maintenance crews (USAF Air Combat Command, 2010). It goes without saying that the assets and requisite resources to support those operations are far from unlimited and personnel resources, particularly RPA pilots, often prove a nontrivial constraint. This inevitably leads innovators to seek out RPA force-multiplying efficiencies to assist in bridging the resource/demand gap. One such efficiency being pursued is simultaneous control of multiple aircraft by a single pilot, or Multi Aircraft Control (MAC). This concept of operations has been documented in the US Air Force UAV flight Plan (USAF, 2009), which calls for future systems in which a single pilot will simultaneously control multiple RPA to enable increased aerial surveillance without increasing pilot manpower requirements. Previous research on the cognitive workload experienced by pilots during MAC indicated that frequent, unpredictable, and oftentimes overwhelming volumes of communication events are able to produce unmanageable levels of system induced workload for

MAC pilots (Schneider and McGrogan, 2011). To further investigate this identified problem, our study makes use of IMPRINT Pro, a Multiple Resource Theory (MRT) based dynamic, stochastic simulation to analyze impacts to cognitive workload by a disciplined communication modality reallocation construct.

2.2 Background

In the RPA domain, communication is a continuous and demanding process. Crews must track information on weather, threats, mission tasking, mission coordination, target coordination, airspace coordination, fleet management, and status and location of any friendly units, etc. The RPA pilot is not only responsible for aircraft control but is also a critical member in a multi-path communications infrastructure (MITRE, 2009). In the ground station, communication with the pilot takes place in one of two modalities: textual chat window(s) or the speech-based radio systems. At any given moment, a pilot may need to monitor multiple chat windows and listen to numerous parties operate over the radio. The multitude of communication sources and different media coupled with the quick inter-arrival rate of these events during a dynamic scenario drives an incredible cognitive workload for the pilot. Cognitive or mental workload expresses the task demands placed on an operator (Beevis et al., 1999). Task demand, or task load, often considers the goals to be achieved by the operator, the time available to perform the tasks necessary to accomplish the goals, and the performance level of the operator (Hardman et al., 2008). Therefore, workload increases when the number or difficulty of tasks necessary to perform a goal increase, or when the times allotted to complete these tasks decrease. Assuming that the operator has a given amount of mental resources (e.g., attention, memory, etc.) that he or she can utilize to complete the necessary tasks, mental workload corresponds to the proportion of the operators mental resources demanded by a task or set of tasks.

Several methods have been employed to measure and quantify mental workload over the past four decades and have been summarized in numerous publications (Beevis et al., 1999; Gawron, 2008; Hardman et al., 2008). The current analysis incorporates Multi Resource Theory (MRT) into the workload calculations to account for channel conflict driven workload. As a theory, MRT purports the existence of four mental dimensions (or channels) available to process information and perform tasks. The channels include the stages of processing dimension, the codes of processing dimension, the modalities dimension and the visual channels dimension. These channels are allocated to concurrent tasks with the difficulty of the tasks and the demand conflict between channels driving the overall mental workload value (Wickens, 2008). MRT falls in line with the concurrent nature of tasks imposed on an RPA pilot (performing primary tasks while communicating and monitoring communication) and is therefore an appropriate theory to apply to the present analysis.

2.3 Method

Having discussed communication events and the incorporation of MRT, it can be seen that the specific channels employed by the modeled communication events will be highly relevant to the MRT workload calculations. As communication events begin to conflict with existing work activities on the various channels, the calculated overall cognitive workload will account for such conflicts. This construct postures the analysis to be able to address the question of whether or not adjusting the intentional allocation of communication events to particular modalities will be able to meaningfully affect overall cognitive workload.

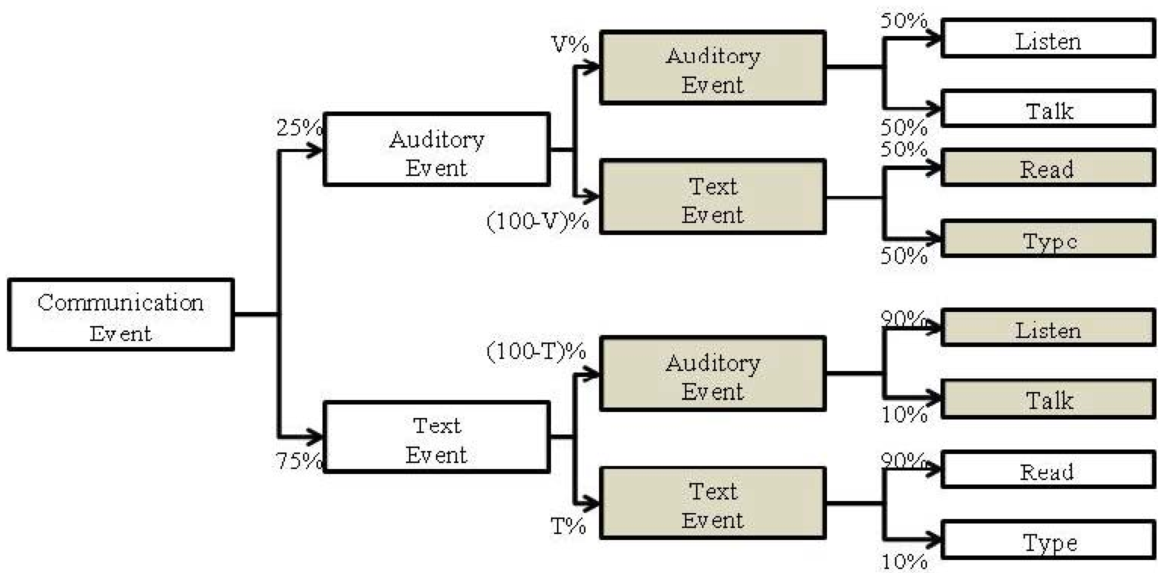
2.3.1 Model.

A previous model of pilot mental workload Schneider and McGrogan (2011) was utilized to understand the impact of communications modality. This model employed functional analysis and task allocation to construct an executable architecture of the multiple RPA system. This architecture was then replicated within the Improved Performance Research Integration Tool (IMPRINT) to estimate the pilots workload under various mission segments, such as handover, transit, emergency, benign and dynamic surveillance, etc. This model relied on Subject Matter Expert (SME) input to develop distributions for the length, frequency, and difficulty of the events that induce workload on the pilot. The original research on this model indicated that workload was particularly high during what were termed dynamic mission segments. These mission segments often involve high levels of communication between the pilot and external actors to facilitate the tracking or observation of moving targets. High levels of communication resulted in particularly high pilot workload while operating a single aircraft and, excessive workload while controlling multiple dynamic-mission aircraft. The original research indicated that a reduction in pilot workload imposed by communication would be necessary to facilitate MAC. To understand the potential impact of communication modality on operator workload, the communications portion of the earlier workload model was modified to permit communications events to be reallocated to alternate communications modalities. The revised model permits communication events that were originally allocated to the auditory channels where the operator listens and speaks to the visual and fine motor channels where the operator reads and types, or vice versa.

Figure 1 depicts the high level structure of the revised communications model. The gray highlighted elements indicate model elements that were added to facilitate this particular evaluation. As shown, in the original communication model, commu-

nication events were generated with a mission segment dependent frequency. As a communication event was generated, it was assigned as either an auditory event or a text-based event with 25% of the events being allocated as auditory events and the remaining allocated as text events. Half of the auditory events then required the pilot to talk or listen while 90% of the text events required the pilot to read while only 10% of the events required the pilot to type a response. Although not shown, it is then assumed that some percentage of the final events generate a repeat communication event, indicative of a continued conversation.

Figure 1. Modified Communication Model of Pilot Workload



To conduct the current evaluation, the auditory and text events shown in gray have the potential to either pass an auditory or text event as a respective auditory or text event or to convert an auditory event to a text event or convert a text event to an auditory event. With this modification, it is assumed that the characteristics of the communication are due to communication needs, such that if a text event in the original model had a 90% chance of providing an input to the pilot and only a

10% chance of an output to the pilot, a text event converted to an auditory event has a 90% probability to require the pilot to listen and only a 10% probability to require the pilot to talk. The parameters V (for Voice reallocation) and T (for Text reallocation) provide the ability to convert auditory or text events to its compliment. If V and T are both 100%, the revised model equates to the original model. Reducing either of these parameters permits a portion of one type of communication event to the converted to the complimentary communication event.

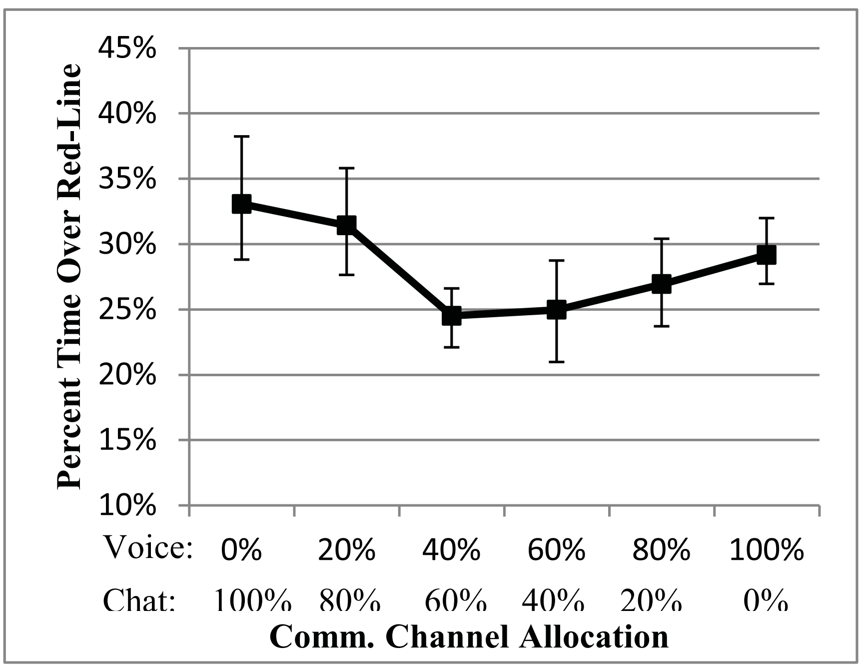
2.3.2 Experimental Design.

For this paper, a total of six "levels" of voice/text allocation were selected such that the percent of voice communication were varied between 0 and 100 percent. For levels of voice communications less than 25%, V was varied while T was maintained at 100%. However, for levels of voice communications greater than 25%, V was maintained at 100% while T was varied to achieve the desired communications levels. All analysis was performed for a 10 hour dynamic mission segment with a single pilot operating the aircraft. Although IMPRINT does not currently have built-in Monte Carlo functionality, an external batch application was developed to replicate numerous runs. A total of 10 replications using different random number seeds were computed to estimate the output statistics. The output of the IMPRINT model was analyzed to determine the proportion of time that the operator would experience workload values over a specified task saturation threshold. A workload value of 60 was calibrated to be about the 90% of operator maximum threshold, which indicates the workload value a pilot can experience without degraded performance. The mean and variance across the 10 replications for each communication ratio was calculated. Analysis of Variance (ANOVA) and Tukey post-hoc tests were employed determine the statistical differences between the average of percent time over threshold.

2.4 Results

Figure 2 shows the percent time over threshold as a function of the percentage of voice communication. A one way ANOVA indicated a significant effect of the percent of voice communication upon the percentage of time over threshold ($P < 0.001$). As shown in Figure 1, the percent of time over threshold is reduced as the percent of voice communication is increased from 0% to 40%. At 40% voice communication the percent time over threshold is reduced to 24.5% compared to 33.1% with 0% voice communication. This change is statistically significant. The change in percent time over threshold is statistically insignificant as the percent of voice communication is increased from 40% to 60%. This trend indicates that pilot workload is reduced by the use of both auditory and text-based communications in this system.

Figure 2. Percent Time Over Threshold as the percentage of voice is reallocated



Results further show that the percent time over threshold is greater at 0% voice than at 100% voice communications. This might have been expected as reading

and typing likely conflicted directly with other tasks being performed by the pilot, including visually monitoring the status and manipulating the controls of the RPAs. As such workload is highest when all of the communication is allocated entirely to the visual channel.

2.5 Conclusions

The model indicates that by deliberately allocating communication between auditory and text-based modalities the pilots workload and particularly the percent of time the pilot operates above their task saturation threshold can be statistically reduced. The model shows that the percent of time over threshold is greatest when all of the communication is allocated to the text-based communications such that zero percent of the communication is allocated to voice. This type of communication is most likely to conflict with other tasks involving the visual system to monitor the RPA and the small motor system, which is used by the pilot to control the RPA. As communication events are moved from text to auditory, the workload decreases. However, as more communication is moved to the auditory channel, the percent of mission time over task saturation threshold then begins to increase. The increase likely occurs as the auditory tasks begin to overlap and conflict with one another to increase workload. There appears to be an optimal allocation of communications between voice and text modalities to achieve the lowest workload given a constant traffic load. Future research will examine dynamic reallocation of modalities.

III. Simulation of Distributed Communication

This paper[1] is formatted for submission to the International Journal of Human Factors Modelling and Simulation.

Discrete Event Simulation of Real Time Human Distributed Team Communication

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Abstract

With increasing automation of Remotely Piloted Aircraft (RPA), the capability for a single operator to fly multiple vehicles may be possible, but improved Human Systems Integration becomes important. These operations rely heavily on distributed team communications determined by the systems architecture. This research investigates the effects of systems architecture on operator workload. The Improved Performance Research Integration Tool (IMPRINT) was used to estimate workload using Multiple Resource Theory for four system configurations simulated in four mission activity levels. Mental workload, monitoring time and the number of delayed tasks were estimated to determine the effect of changing the number of communication nodes and greater automation of navigation tasks. Operator interviews provided stochastic parameters for the model. The analysis demonstrates that removing the navigation tasks has a greater effect on task delay and time spent building situation awareness (SA) than changing the number of communication nodes during high load mission segments. Changing the number of communication nodes has a greater effect on mental workload than exclusion of the navigation task. System architecture changes have

[1]This paper was written in UK English

little effect for mission segments with low load. This research has implications for future design of RPA or distributed team systems.

3.1 Introduction

The demand for increasingly complex medium altitude remotely piloted aircraft (RPA) platforms and their maturing capabilities has brought with it an increased reliance upon distributed team communications. Many U.S. government organizations, such as the military services, Border Patrol, NASA (NASA, 2011) and the Department of Homeland Security, have requirements for RPA technology and have an expressed interest in expanding their respective fleets of RPAs. Civil uses for RPAs abound (U.S. Government Accountability Office, 2008). However, real time communication can be burdensome in intense situations, and it can affect the ability of the pilot and sensor operator to perform their respective primary tasks. Offloading of communication can keep the RPA operators from becoming task saturated (Wickens et al., 2003). Communication offloading is accomplished in current U.S. Air Force (USAF) operations by the addition of mission intelligence coordinators (MIC) who serve to facilitate external communications. This research uses a cognitive model to predict MIC workload and inform future communications architecture development for remotely piloted systems.

In the USAF, network technologies in RPA systems have increased the number of communication tasks that operators must perform. As a result, operators communicate with more parties more often than with previous radio and land-line telephone technologies. In situations where both high volumes of communication and high operator workload exist, there may be a correlation between communication and workload. The hypothesis of this research is that the current communications architecture induces high task demand, and resultant workload on the operator. The primary

research question is: *How does communication architecture affect the workload experienced by a system operator?*

A military example was examined to answer this question. This example is extensible to future civil and commercial systems, some of which already use similar systems. Implications of this research are important for designing new systems which require extensive communication between distributed teams requiring real-time communication. Real-time distributed communication is a cornerstone of military strength and a boon to many organizations who use or plan to use RPAs; this research addresses ways in which communication architecture could be improved to allow for more effective real time distributed communication.

3.2 Background

The background of this research combines literature from several otherwise disparate fields of study in an attempt to bridge the gaps between them and provide a solid foundation for analysis. First, the premise of workload modelling and its relevance to systems design will be discussed. Background information about the military example will then be given along with relevant architecture diagrams.

Mental workload is the characterization of limited human mental resource demands (Cain, 2007; Wickens and Yeh, 1986). For the purposes of this research, mental workload is a unit-less and relative measure derived from the combination of tasks imposed on the human, their respective mental resource demands and the degree to which the tasks place demands on conflicting or complimentary cognitive channels (Wickens and Yeh, 1986; Wickens, 2008). Multiple resource theory (MRT) is the concept that human cognitive resources are divided into multiple attentional 'pools', which are taxed differently depending on task load. Studies showing the extent to which time sharing or multitasking situations use different cognitive processing struc-

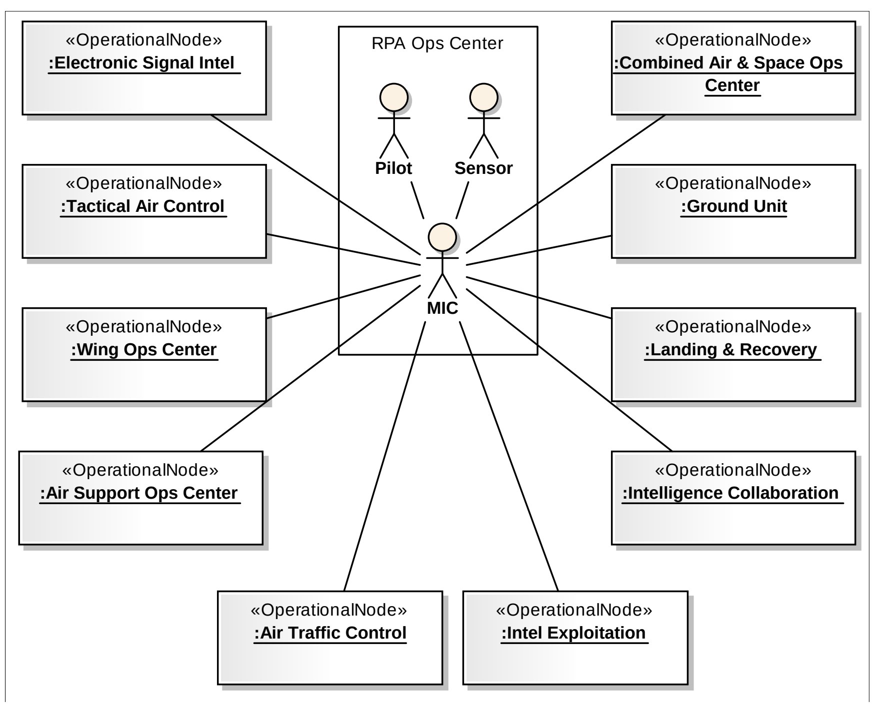
tures provide scientific evidence for the validity for this theory. A multi-dimensional model of MRT is given in (Wickens, 2008). The model is essentially an input-process-output model of human perception, cognition and action with resource distinctions drawn along modal lines. The codes and modalities of processing distinguish among resources used for sensory input and working memory. The codes of processing are spatial and verbal, while the modalities are auditory and visual. The codes and modalities represent the combinations in which humans perceive information. They are spatial-auditory, spatial-visual, verbal-auditory and verbal-visual. The stages of processing represent the modalities of cognitive process resources which are used to select and execute action, and the responses are manual-spatial or vocal-verbal. This study examined operator workload for verbal codes of processing, both modalities, and vocal-verbal responses. For example, when an operator receives and sends chat messages, she perceives them using verbal-visual resources, processes them using vocal-verbal resources, and responds using vocal-verbal resources.

The method used in this research to predict mental workload using MRT and discrete event simulation is found in Keller et al. (2002). Schneider and McGrogan (2011) used the Improved Performance Research Integrated Tool (IMPRINT) to implement the method described in Keller et al. (2002) to predict RPA pilot mental workload. Workload predictions were used to understand the manpower implications of multiple aircraft control. To develop the mental model of the pilot, Schneider and McGrogan created executable architecture to translate the system design into a dynamic model. Wang and Dagli (2008, pg. 1) notes that "Architecture modeling furnishes abstractions for use in managing complexities, allowing engineers to visualise the proposed system and to analyze the problem domain and describe and specify the architecture for the solution domain." Architecture modelling methods were used by Schneider and McGrogan and Mitchell (2000). Schneider and McGrogan's findings suggest that

communication is a major source of workload for RPA operators. Mitchell found that IMPRINT predictions of communication times and frequencies correlated with recorded communications amongst a platoon of soldiers during a simulated mission.

The architecture modelled in this research is that of U.S. RPA communications, centered around the MIC, who is part of a distributed team coordinating to complete remote surveillance missions. According to subject matter experts (SME) there are, during any given mission, between 10 and 15 external organizations with which the MIC must communicate regularly; each of these constitutes one network 'node'. The RPA crew includes a pilot, a sensor operator, and a supervisor. The MIC provides a communication buffer between the crew and the other organizations in the communication network. A diagram of representative nodes in the system is given in Figure 3. The MIC works in the RPA Operations (Ops) Center. The connections between external nodes, the pilot, and sensor operator are not shown.

Figure 3. Diagram of System Nodes



Selection of an appropriate modelling tool that supported calculation of human

mental workload was crucial to the understanding architectural effects on communication induced workload. IMPRINT[2] was selected because of its extensive human performance modelling capability. An executable system architecture model can be built within IMPRINT using a functional decomposition to describe task times and resource demands. IMPRINT provides a common ground between executable systems architecture and analytical workload modelling. IMRPINT was developed by the US Army Research Laboratories to support manpower and personnel systems analysis, but provides the ability to estimate human mental workload. This tool is a dynamic, stochastic, discrete event network modeling tool based on the Micro Saint Sharp modeling language (USARL, 2010).

The creation of an IMPRINT model requires the functional decomposition and allocation of tasks to users or crew members. Workload values are then assigned, following the process described in Keller et al. (2002), to each resource/interface pair and then to each task performed by the user. Mental workload values are calculated based upon multiple resource theory (MRT), which permits the modeling of the effect of both sequential and concurrent tasks upon human mental workload (Wojciechowski, 2006; Mitchell, 2003). As the model runs, single task demand values are calculated for each task performed by the user. When multiple tasks are provided to the user concurrently, competing for limited attentional resources, conflict values are determined based upon the user's ability to perform these concurrent tasks. Task demands which lead to conflict produce nonlinear increases in system induced workload as more tasks are added. The algorithm which IMPRINT uses to calculate mental workload is a combination of a task-resource assignment method (Keller et al., 2002) and a complex, dynamic set of summations (Mitchell, 2000).

To construct an IMPRINT model, users, tasks, task arrangement, task times,

[2] Version 3.1.0.86

task difficulties, and likely errors must be determined. Each of these model elements can be deterministic or stochastic in nature. The discrete events in the model then represent real events and permit a real-time trace of system-induced workload. One of the important features of IMPRINT is the behavior of the model during times when the operator is task saturated and unable to simultaneously address all of the overlapping tasks that are allocated. IMPRINT provides many options, including computing workload with the assumption that the operator will complete all tasks even when the workload is beyond their ability. Workload mitigation strategies may also be modelled, representing ways in which real users might allay the effects of task overlap and overload. There are four strategies available. When a new task in the task queue would cause workload to rise above a preset threshold, the user may be modelled as offloading the new task to a contingent operator, delaying the new task, dropping the new task from the queue completely, or interrupting the current task to perform the new task and completing the first task in a window of opportunity.

3.3 Methodology

Four MICs were interviewed to gather input data for the mental workload model. All four MICs were operationally qualified, 2 were enlisted and 2 were officers, each with more than two years of operational experience. The first part of the interview addressed the logical architecture of the system. The questions were designed to give insight into the MICs' primary goals, major functions, and the order in which tasks are performed. These questions also elicited the relationships between major tasks and external events. The second part of the interview addressed specific tasks, their respective durations and their respective difficulties and derivative tasks. The interview questions were designed to depict all tasks which the MIC performs during a typical shift.

Data from this effort indicated that during a typical shift, the MIC's primary goal is to perform the tasks which are assigned in the pre-mission brief. Typically, these include posting way-point coordinates in a navigation system visible to nearly all operators in the area, relaying important information between the pilot and the other nodes, referencing the mission plan, and acting as an auxiliary monitor of the full motion video (FMV) feed from the RPA. The MIC also maintains the mission report for the entire mission and updates it between tasks.

3.3.1 Choice of Dependent and Independent Variables.

Three dependent, two independent, and one system variable were selected to define the model. Mental workload, monitoring time and the number of delayed events are the dependent variables while the number of external communication nodes and exclusion of navigation tasks are independent variables. The arrival rate of units of activity is a system variable used to compare the effects of the independent variables across four mission task loading scenarios.

The mean exponential interarrival time of major events, λ_{maj}, was assigned four levels: 30, 60, 120, and 1200 seconds to represent the variable and unpredictable nature of real missions. SMEs described missions ranging from overwhelming task loads (represented by $\lambda_{maj} = 30$) to nearly abject boredom (represented by $\lambda_{maj} = 1200$). The levels between were selected arbitrarily to provide more resolution near the busy end of the scale. The number of communication nodes with which the MIC must communicate is represented by n_{comm}, and the control value of ten is derived from Figure 3. The navigation task parameter, Nav has two levels, on and off, to represent the inclusion (on) or exclusion (off) of the navigation tasks in the model. The simulation length, T_E, was set to 7200 seconds, or two hours. Two hours was selected as the length at which the system exhibited stable behavior, and variance

between simulation runs was very low for workload observations.

Mental workload was selected as a dependent variable because of its relevance to system design. The system modelled in this research primarily requires cognitive work more than physical work. Mental workload values are calculated using difficulty ratings for individual tasks, the cognitive resources which those tasks require, the presence of other tasks, and how much the required resources conflict between the multiple tasks. Delayed task count is a count of all the tasks which needed to be delayed by the operator because workload was over a certain threshold, or 'red line'. IMPRINT allows users to model both system induced workload with no notion of the operator and the workload experienced by the operator. All of the conditions described in the design of experiments were run again with a workload management strategy, which simulates an operator present who would "[p]erform tasks sequentially, beginning with ongoing tasks and then performing the next task" (Mitchell, 2000; Alion Science and Technology, 2011). The delayed task count shows how many of the tasks during the mission might have been delayed because of high workload.

It is assumed that the operator will monitor up to six computer monitors to detect changes in information displayed through two networked computer systems during any available time between other tasks. Monitoring time is the sum of the durations of monitoring tasks over the course of the two hour mission segment. Specifically, the monitoring tasks are composed of monitoring a FMV feed, a navigation system, and up to 15 IRC windows. Monitoring the navigation system is considered both a navigation task and a monitoring task for the purposes of this research. Monitoring time represents the ability of the MIC to complete the secondary task of maintaining situation awareness (SA). SA is defined as the perception and understanding of one's environment and the ability to predict the status of the environment in the near future (ENDSLEY, 1995; Tsang and Vidulich, 2002). The MICs ability to maintain

an accurate picture of the operational environment is very important to the other members of the team; system monitoring time is a measure of the ability to allocate time to this task.

3.3.2 Experimental Design.

The analysis follows a fractional factorial design where each level of n_{comm} and Nav are compared at each level of λ_{maj} for each of the three metrics. For a full analysis of the effects of the independent variables, sixteen mission conditions were modelled. Each of these sixteen conditions was run five times with workload management strategies 'on' and another five times with workload managements strategies 'off'. The presence or absence of workload management strategies was not considered an independent variable; replications with the strategies employed were used to count the number of delayed tasks. The experimental conditions are listed in Table 1.

Table 1. List of Conditions

Condition ID	λ_{maj}	n_{comm}	Nav. Task
1	30	10	on
2	30	10	off
3	30	6	on
4	30	6	off
5	60	10	on
6	60	10	off
7	60	6	on
8	60	6	off
9	120	10	on
10	120	10	off
11	120	6	on
12	120	6	off
13	1200	10	on
14	1200	10	off
15	1200	6	on
16	1200	6	off

The number of replications was determined by following the process outlined in Banks et al. (2010). Using condition 1, which was thought to be the most variable, the desired half-widths of the confidence intervals were obtained by completing five replications for each of the sixteen conditions, resulting in 160 independent replications. Results were calculated for five random number seeds between 1 and 1000 using a random integer generator function in MATLAB. The half widths were deemed sufficient if they included no more than ±5% of the mean.

Data groups were compared for purposes of determining meaningful effects. Of the large set of possible pairwise comparisons, only sixteen were made to determine the significance of the four system configurations. The two control groups, where $n_{comm} = 10$ and $Nav =$ 'On' were compared pairwise with the alternate groups, where $n_{comm} = 6$ and $Nav =$ 'Off'. These four comparisons were made at each of the four levels of λ_{maj}.

3.4 Model Description

3.4.1 Assumptions.

It is assumed that a 'unit' of activity, such as the observation of a single suspicious action performed by the surveillance target, constitutes a major event and causes the MIC to perform communications once for each node in the external system. The performance of one communication task, e.g. internet relay chat (IRC) or intercom use, constitutes a minor event. The assumption that one minor event occurs for each node for each major event is valid for the following reasons: 1) it was reported by SMEs that all of the mission related communication occurs because of external events, 2) interviews revealed that during high communication situations, MICs find themselves communicating 'constantly', presumably more often than once per node per external event. Therefore, the estimate of one communication per node per major

event is a valid assumption. The model assumes that each major event triggers one minor communication event for each node.

Another important assumption is that the system would demand that the MICs handle these communication events sequentially and not simultaneously. Interviews revealed that when MICs would communicate with some nodes, they would sometimes not receive a response for up to five minutes, meaning that for most of their communications, response time is not critical within a reasonable window. The interviewees also noted, however, that they communicated constantly during major events. The duration of major events is increased or decreased by adjusting the exponentially distributed interarrival times of minor events, λ_{comm}, which represents the rate at which the system requires the MIC to complete communication tasks. It was also reported that for a single unit of activity, it took approximately twenty seconds for the communications to stop. To accurately model the interarrival of minor communication events, the author modelled a single major event and ten nodes. Experimentation with the interarrival time of minor communication events led the author to an assumed exponential arrival rate of one every three seconds to achieve the twenty second duration of major events. Therefore, λ_{comm} is set to three seconds for the purpose of this research.

The model includes only the lower level tasks which were determined to be critical to the communication functions of the MIC. The tasks included in the model are three monitoring tasks, three sequential tasks related to posting coordinates into the navigation system, as well as reading, typing, listening and speaking both complex and simple sentences. The model has represented within it fourteen total MIC tasks. The tasks are arranged within the model according to the information given in the interviews and in existing architecture. Task durations and difficulties were assigned conservatively using the visual, auditory, cognitive and psychomotor (VACP) rating

scales within IMPRINT (Keller et al., 2002; Alion Science and Technology, 2011).

3.4.2 Structure and Logic.

There are two types of tasks in the model, automated tasks which are not included in the workload calculation, and operator tasks, which do carry workload values. The model boundaries are defined by the operator tasks, which are detailed in Table 2, where normal distribution values are given as μ, σ and triangular values are given as mode, min, max. The structural tasks represent the system which is external to the model boundary. Only tasks performed by the MIC are included explicitly, while external stimuli, which may represent the actions of other operators, are abstracted to the tasks which they induce the MIC to perform. These external stimuli are represented as entity generating 'dummy' tasks which generate MIC tasks according to the logic stated above. On its foundational structural level, the model is a queueing system where entities arrive with exponentially distributed rates, and are 'processed' by tasks with normally distributed processing times. These entities represent the external events. Network edges or stochastic logical code executed during the tasks determines the entities' next destinations.

Table 2. MIC Low-Level Tasks

Task	Duration Distribution	Duration (seconds)	Single Task Demand
Monitor Navigation System	Triangular	6, 4, 9	5.0
Monitor FMV	Triangular	10, 3, 21	6.0
Monitor mIRC	Triangular	6, 4, 9	5.0
Copy Coordinates From mIRC	Normal	1.0, 0.25	8.5
Find Navigation System Monitor	Normal	1.0, 0.25	4.0
Paste Coordinates into the system	Normal	1.0, 0.25	8.5
Read Simple Sentence	Normal	2.0, 0.5	5.1
Type Simple Sentence	Normal	1.5, 0.5	7.0
Listen to Simple Sentence	Normal	2.0, 0.5	3.0
Speak Simple Sentence	Normal	1.5, 0.5	2.0
Read Complex Sentence	Normal	7.0, 2.0	5.1
Type Complex Sentence	Normal	6.0, 2.0	7.0
Listen to Complex Sentence	Normal	7.0, 4.0	6.0
Speak Complex Sentence	Normal	5.0, 2.0	4.0

3.5 Analysis & Results

3.5.1 Methods of analysis.

Data for each metric was tested for normality; comparison groups were tested for significant differences. All confidence intervals are calculated at $\alpha = 0.05$. Lilliefors tests were conducted on replication means within groups to determine normality. [3] Three-way analysis of variance (ANOVA) tests were performed on group means to determine which changes had significant effects on the dependent variables. Post-hoc tests were conducted for added specificity about the differences between conditions.

Distribution of Workload Data. For a given replication, the weighted mean of workload values where w_i represents workload and d_i represents the duration

[3] The Lilliefors test was used because it is valid for small sample sizes, where the chi-square test is not as useful (Lilliefors, 1967). Also, the Lilliefors test is non-parametric, thus the parameters for the normal distribution against which the sample is tested do not need to be given as they would be for the one-sample Kolmogorov-Smirnov (KS) test.

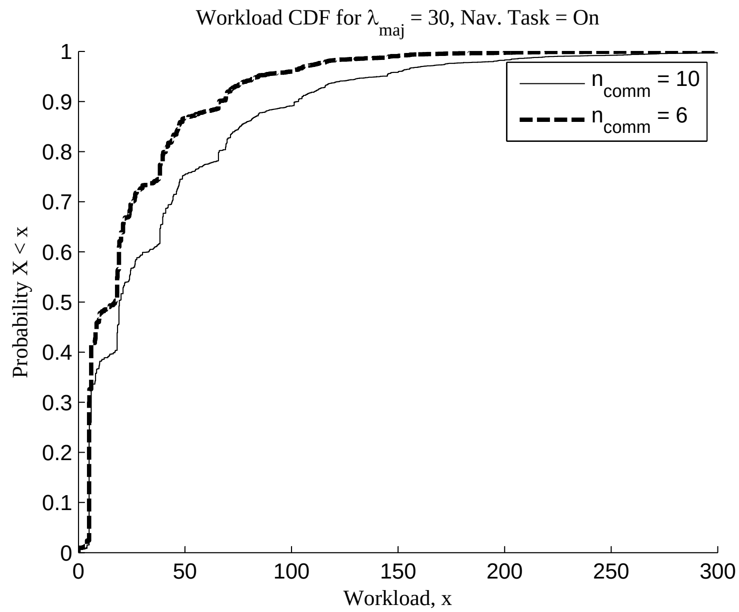
at that workload value is computed by Eq. 1.

$$\bar{w} = \frac{\sum w_i \cdot d_i}{\sum d_i} \tag{1}$$

Lillefors tests were performed on each condition to test for normality. Data which is normally distributed is considered to be the result of a random process, and can statistically tested as such. The approach used in Eq. 1 to estimate the means was conducted with the understanding that each shape is different by design. In other words, because the groups are being compared at levels of λ_{maj} each group has a similar set of workload spikes and flat periods where low workload occur, though they occur at different times during the mission within each group. The replications within each group are similar enough that differences between groups are easily seen from ANOVA tests, but there is some doubt cast on these tests because of the insensitivity of weighted averages to equal changes in area under the workload function. Therefore, an additional test was warranted.

To determine whether there were differences between the conditions, two rounds of two-sample (KS) tests were conducted. The two-sample KS test computes the distance between the empirical distribution functions (CDF) of the two samples. Because two empirical CDFs are being compared, the two-sample KS test is non-parametric. The null hypothesis for the two-sample KS test is that the two samples come from the same continuous distribution. The null hypothesis is rejected if the distance between the two functions is sufficiently large (Darling, 1957). Within each group, the replications were compared pairwise to determine whether each replication within the group came from the *same* continuous distribution. A second set of two-sample (KS) tests was performed across comparison groups to determine whether the groups came from *different* continuous distributions. A comparison of two conditions is shown in Figure 4.

Figure 4. Workload CDF for Two Groups



Monitoring Time & Delayed Tasks. The means of the monitoring times for each condition were normally distributed within each group. Delayed task counts were also normally distributed within each group.

3.5.2 Results.

3.5.2.1 3 Way Analysis of Variance Tests.

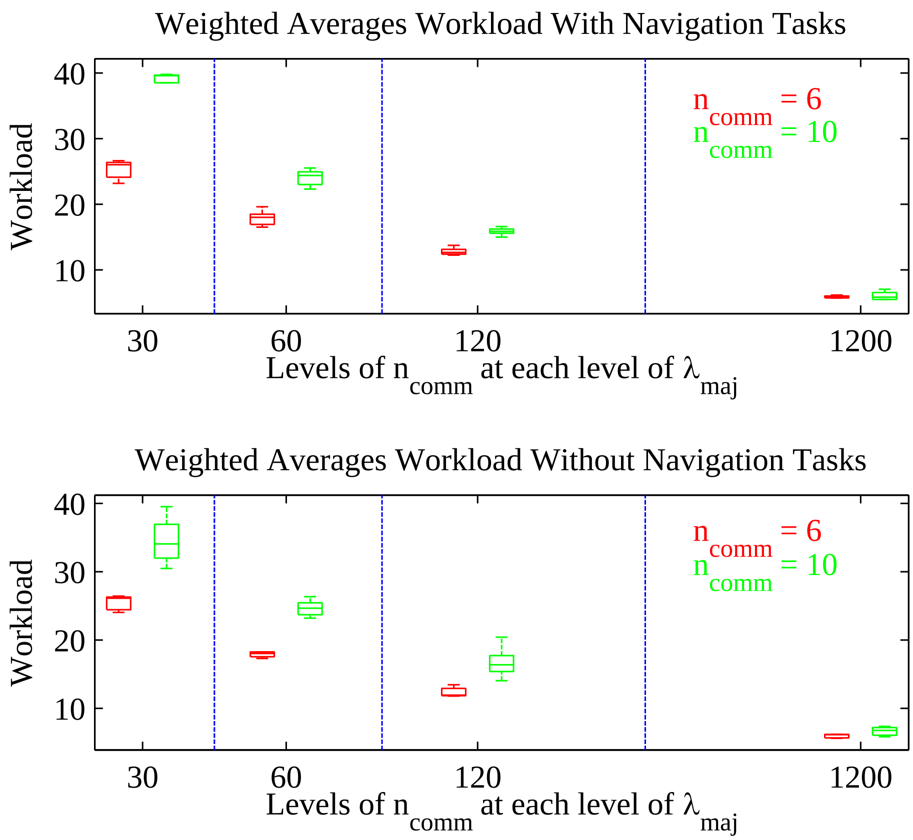
Each of the three-way ANOVA tests showed that the largest contributor of variance was λ_{maj}. This was expected; λ_{maj} changes the mission scenario and the essential shape of the workload function. Only the effects of n_{comm} and Nav are discussed. In each case, λ_{maj} exhibited two-way interactions with the other two variables. The interaction is due to the design of the model; decreasing λ_{maj} necessarily decreases the number of n_{comm} events and the number of times the Nav task was executed in the Nav = 'On' cases. In other words, λ_{maj} was purposely linked to the other variables in an indirect way.

The three-way ANOVA test for workload showed that n_{comm} had a significant effect on weighted workload averages between groups ($\mathrm{F} = 337.1, \mathrm{P} < 0.0001$). Nav was found to not have a significant effect. There was a small three-way interaction between λ_{maj}, n_{comm}, and Nav ($\mathrm{F} = 5.634, \mathrm{P} < 0.0001$). For monitoring time, the three-way ANOVA test showed that n_{comm} had a significant effect between groups ($\mathrm{F} = 49.38, \mathrm{P} < 0.0001$). Nav was found to have a much greater effect ($\mathrm{F} = 822.39, \mathrm{P} < 0.0001$). There were no other two or three-way interactions. The three-way ANOVA test for the delayed task count showed that n_{comm} had a significant effect between groups ($\mathrm{F} = 93.59, \mathrm{P} < 0.0001$). Nav was found to have a slightly greater effect ($\mathrm{F} = 102.40, \mathrm{P} < 0.0001$). There were no other two or three-way interactions.

3.5.2.2 Workload.

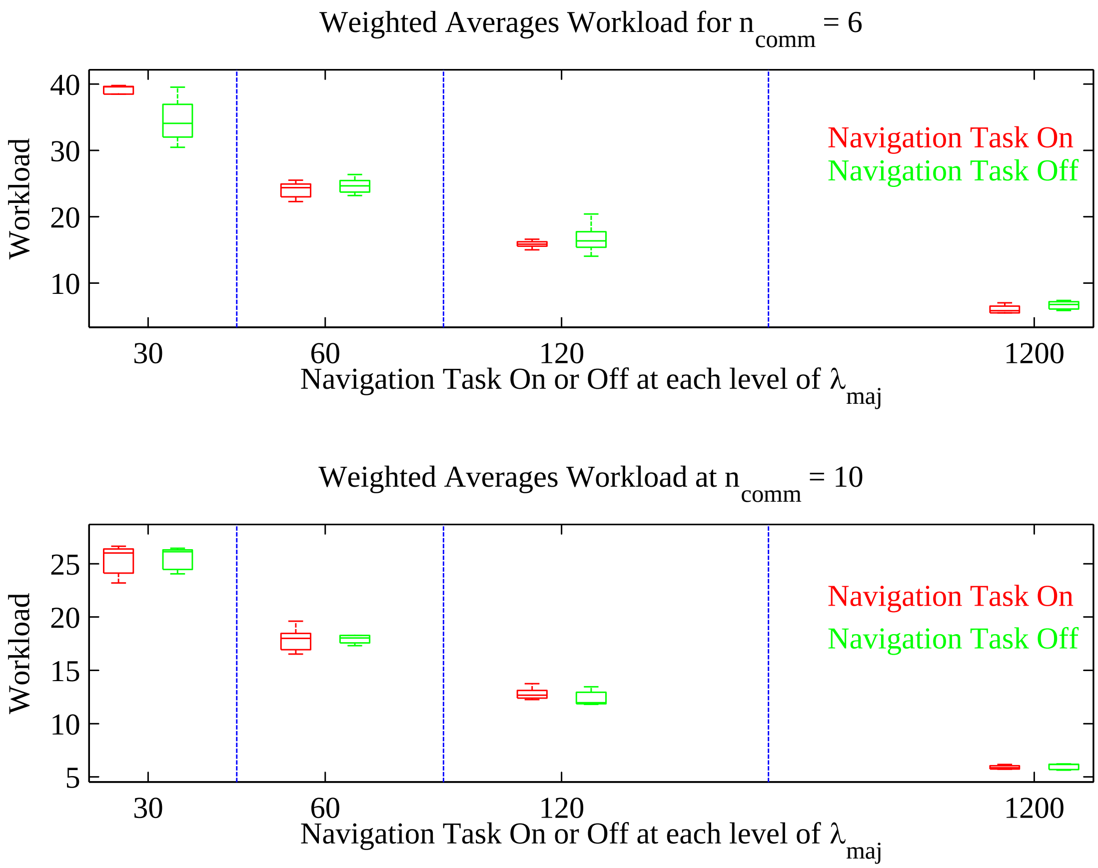
Results for workload were mixed. KS tests within groups showed that several conditions were not composed of replications from same continuous distributions. These replications were removed before the between groups KS tests were conducted.

Figure 5. Weighted Workload Mean Comparison 1



The effect was greater in the conditions with the navigation task included. Post-hoc tests showed that changing levels of n_{comm} was only significant for λ_{maj} of 30, 60, and 120 seconds. The post-hoc tests showed that the exclusion of the tasks was only significant in one comparison, at $n_{comm} = 10$ and $\lambda_{maj} = 30$. Figure 5 and Figure 6 show how changing levels of n_{comm} and Nav affect weighted mean workload.

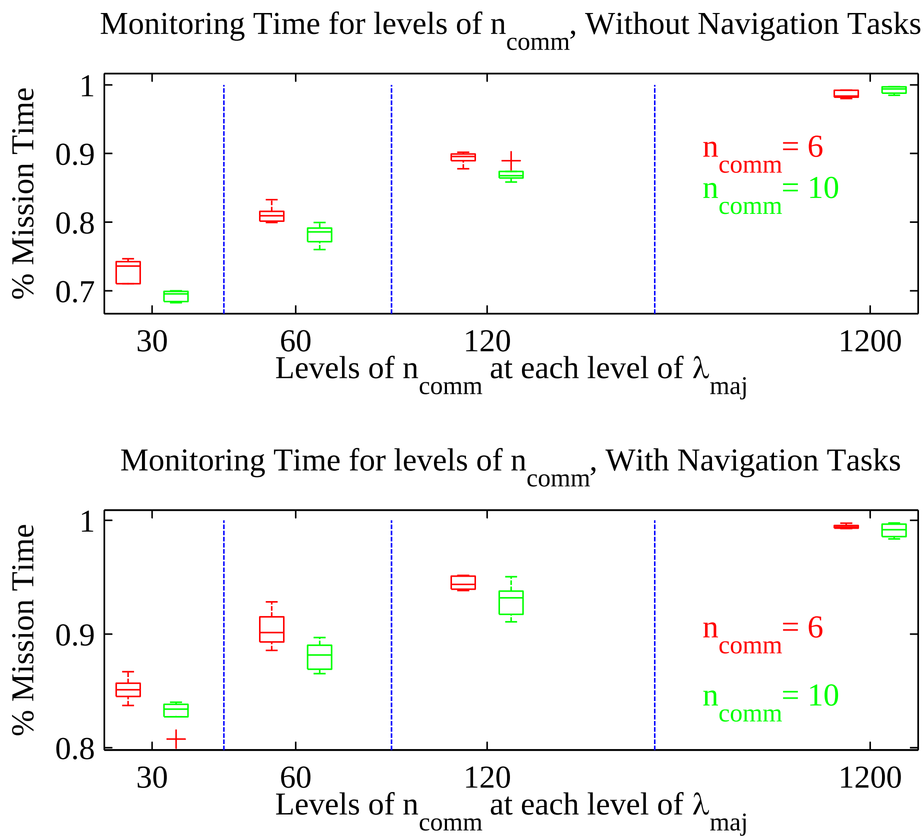
Figure 6. Weighted Workload Mean Comparison 2



3.5.2.3 Monitoring Time.

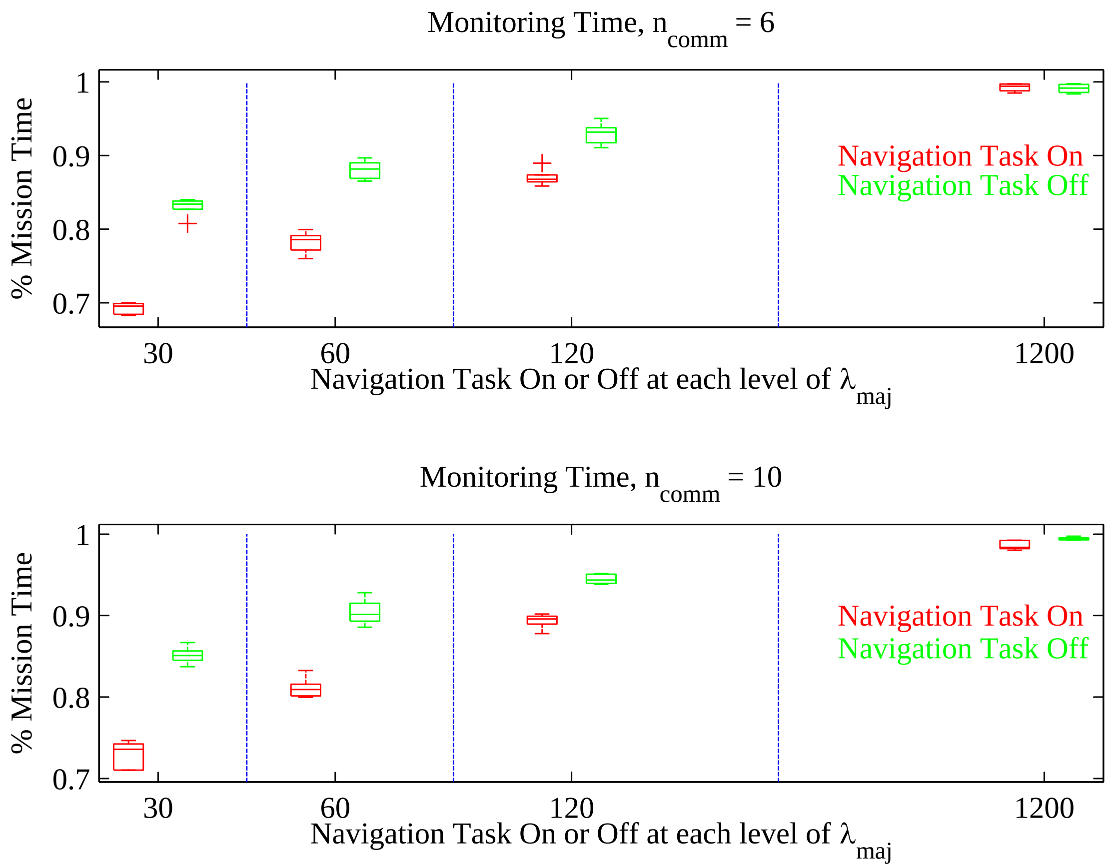
Monitoring time results showed that changing levels of n_{comm} had a greater effect when the navigation tasks were included in the model. This is partly due to dependency of the metric on the measurement of these tasks. Changing the number of communication nodes with the navigation task excluded was significant in only one of the four comparisons, for $\lambda_{maj} = 60$. The effect of changing n_{comm} can be observed in Figure 7.

Figure 7. Monitoring Time Comparison 1



Post-hoc tests showed that excluding the navigation tasks was significant for λ_{maj} of 30, 60, and 120 seconds. The effect of excluding the navigation tasks can be observed in Figure 8.

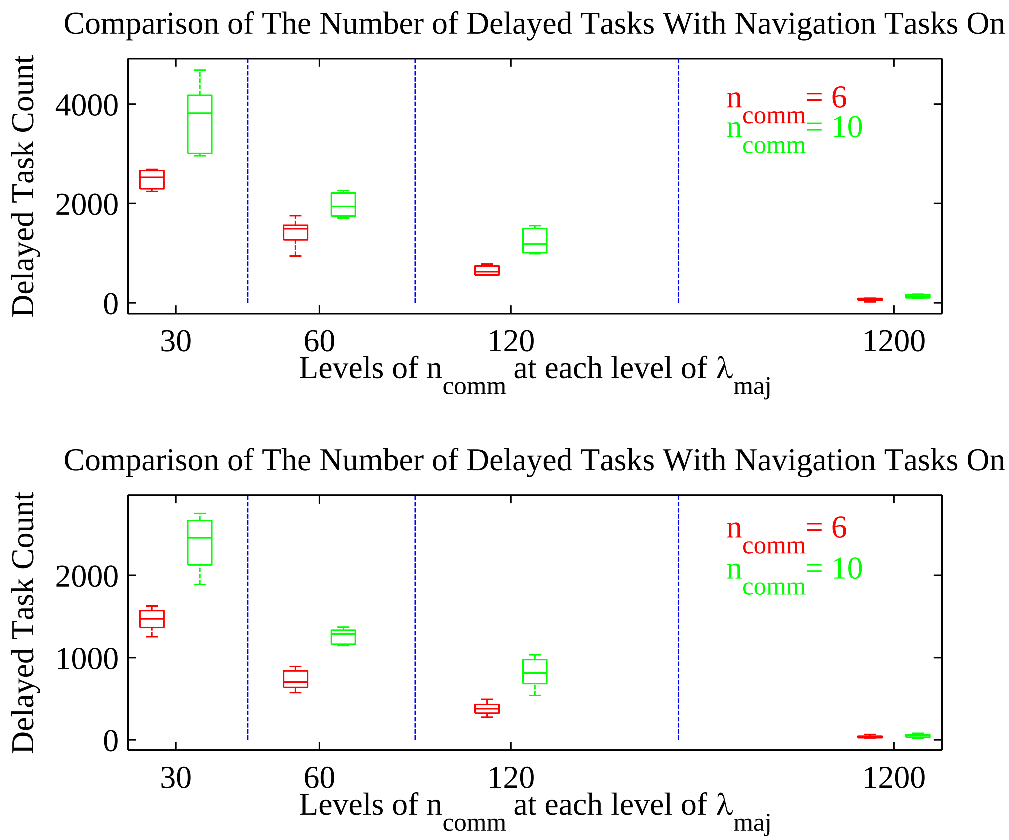
Figure 8. Monitoring Time Comparison 2



3.5.2.4 Delayed Events.

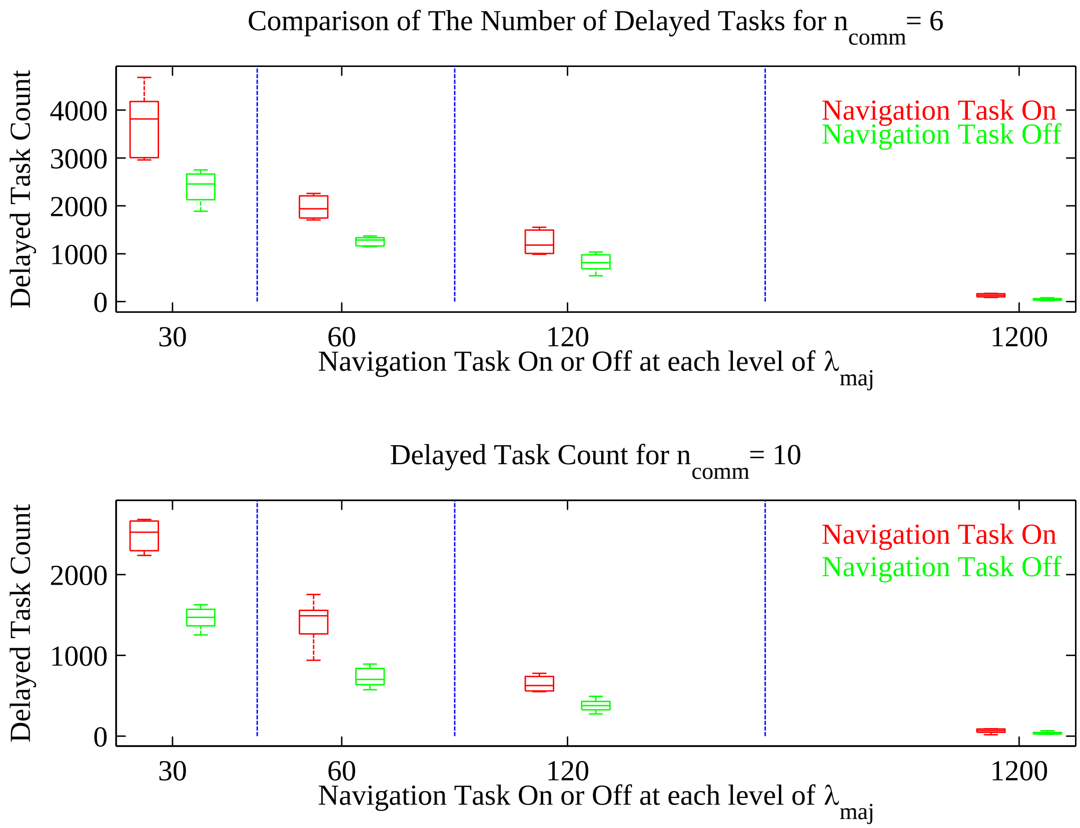
Post-hoc tests revealed that the effect of reducing the number of communication nodes on the number of delayed events was significant for λ_{maj} of 30 seconds in the Nav = 'On' condition. In the Nav = 'Off' condition, changing the level of n_{comm} was significant to the changes in mean for λ_{maj} of 30, 60, ad 120 seconds.

Figure 9. Delayed Task Comparison 1



The post-hoc tests also showed that exclusion of the navigation tasks had a significant effect on the number of delayed tasks for both levels of n_{comm} for λ_{maj} of 30 and 60 seconds. The effect of reducing the number of communication nodes is shown in Figure 9, while the effects of excluding the navigation tasks are shown in Figure 10.

Figure 10. Delayed Task Comparison 2



A multiple comparison of means post-hoc procedure was conducted using the statistics from the three-way ANOVA tests. The test returns a Bonferroni adjusted probability that the means are not significantly different. Percent improvement was calculated using results from the post-hoc tests by calculating the change in mean for system changes that resulted in statistically significant improvements in each of the three metrics. These improvements are shown in Table 3. Bold type signifies values which were significant in post-hoc tests.

Table 3. System Improvements

Workload	Monitoring Time	Delayed Tasks	Change	Constant	λ_{maj}
35.42%	**5.28%**	**32.84%**	Change Nodes from 10 to 6	*Nav* On	30
24.41%	**3.96%**	22.53%	Change Nodes from 10 to 6	*Nav* On	60
19.35%	**2.69%**	47.76%	Change Nodes from 10 to 6	*Nav* On	120
2.58%	0.00%	50.46%	Change Nodes from 10 to 6	*Nav* On	1200
26.18%	**2.49%**	**38.79%**	Change Nodes from 10 to 6	*Nav* Off	30
27.35%	**2.72%**	**42.01%**	Change Nodes from 10 to 6	*Nav* Off	60
25.94%	1.68%	**53.45%**	Change Nodes from 10 to 6	*Nav* Off	120
10.36%	0.33%	18.57%	Change Nodes from 10 to 6	*Nav* Off	1200
11.89%	**19.97%**	**35.44%**	Change *Nav* from On to Off	n_{comm}=10	30
0.00%	**12.60%**	**36.13%**	Change *Nav* from On to Off	n_{comm}=10	60
0.00%	**6.79%**	34.33%	Change *Nav* from On to Off	n_{comm}=10	120
0.00%	0.00%	63.98%	Change *Nav* from On to Off	n_{comm}=10	1200
0.00%	**16.79%**	**41.16%**	Change *Nav* from On to Off	n_{comm}=6	30
0.00%	**11.54%**	**48.27%**	Change *Nav* from On to Off	n_{comm}=6	60
3.32%	**5.75%**	41.47%	Change *Nav* from On to Off	n_{comm}=6	120
0.00%	0.83%	40.80%	Change *Nav* from On to Off	n_{comm}=6	1200

Generally, changing the system architecture resulted in greatest improvement during periods of high event frequency ($\lambda = 30, 60$ seconds). Little improvement is shown for changing the system during periods of low event frequency ($\lambda = 120, 1200$ seconds).

3.6 Discussion

3.6.1 Conclusions.

Mental workload in a system of distributed teams can be lessened at the system level by reducing the number of network nodes with which the operator must communicate frequently. Mental workload can be decreased to a lesser extent by decreasing the number of secondary tasks which the system requires the operator to perform. Reducing the number of secondary tasks has little to no significant effect

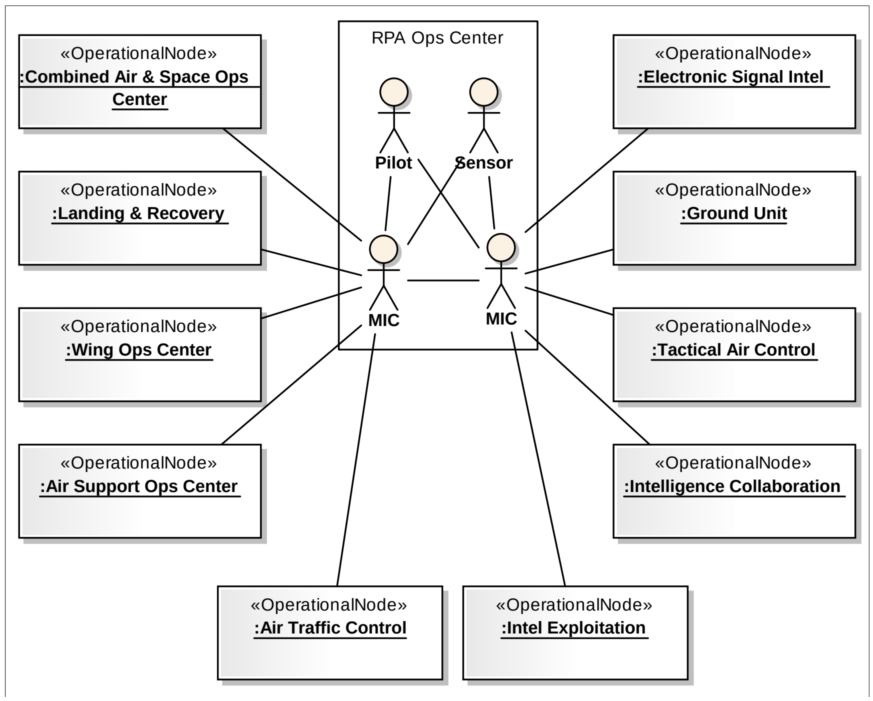
on mental workload if the number of communication nodes is already low. For future systems, therefore, it would be more beneficial to focus design on reducing the operator's communication nodes rather than ensuring that the operator had no secondary tasks. Additionally, creating an additional node to handle more communication is most useful for systems which generate communication events with high frequency, in this case, 10 per 30 seconds.

The amount of time which the operator can use to monitor the system and build valuable situation awareness is increased effectively by reducing the number of communication nodes or reducing the number of secondary tasks. If the secondary tasks include monitoring tasks, reducing the number of communication nodes has little effect if these tasks are already excluded. Reducing the number of communication nodes and exclusion of secondary tasks both have significant effects in systems with high frequencies of communication-inducing events. Reducing the number of communication nodes is more effective if there are no secondary tasks. Reducing the number of secondary tasks was effective for systems with both levels of communication nodes at the two higher levels of communication-inducing event frequency, implying that reducing secondary tasks reduces the probability that tasks will be delayed.

The effective number of communication nodes can be reduced in at least three ways. This research assumes that a second operator has been introduced in the $n_{comm} = 6$ conditions, and has taken half of the first operators communications nodes. This configuration is shown in Figure 11. The first operator loses five of the original nodes and adds one node, which is the second operator, giving a total of six nodes to each operator, in which case, the original operator is modelled as simply having four fewer nodes. The nodes in Figure 11 have been reallocated such that each MIC communicates with a somewhat related set of nodes. Tactical and intelligence gathering organisations are connected to one MIC, while air traffic con-

trol and authority organisations are allocated to the other. These allocations would ideally change dynamically to avoid one MIC being overwhelmed while the other is bored. This allocation organises information according to the operator's goal, and thus promotes situation awareness (Endsley et al., 2003).

Figure 11. Alternate Diagram of System Nodes With Two MICs



Another way in which the reduction of communication nodes can be achieved is through automation. The interviewees reported that about one half of the communication tasks they perform involve the simple passing of information from one party to another. If this task could be automated using software which filters the chat stream and passes information between the correct parties, the effective number of nodes would be reduced. A third way to reduce the number of communication nodes is to reduce or combine organizations in the external system. The method by which this could occur is well beyond the scope of this research, but the effect on the operator would be a reduction in the number of organizations with which they would have to communicate, presuming that the newly combined organizations would communicate

more effectively within themselves.

In this system, the navigation task represents what would be secondary tasks in other systems. Offloading secondary tasks during periods of high mental demand can be accomplished with automation, which is already being instituted in the military example modelled for this research. A software tool called "Internet Relay Chat Coordinate Extractor (ICE)" is being implemented in a few operational units, according to SMEs. The automation could be tied to the cognitive arousal of the operator, however and switched off during periods of low demand to allay boredom. Secondary tasks could also be offloaded to a contingency operator, as manpower availability dictates.

3.6.2 Future Work.

Future work should define the turn-taking system of conversation in the military environment. A well defined turn-taking system would give a more pedigreed foundation upon which future communications models could be built. Investigations should also be conducted on the effects of changing the external system on the operator at an enterprise level.

Acknowledgements

The authors would like to acknowledge the active duty military members and contractors at Creech Air Force Base, NV, whose input proved invaluable to this research. These operators and test personnel sacrificed a great deal of precious time to grant interviews and expertise to this project. The authors would also like to thank Mr. Robert Sargent and the employees of Alion, Inc., for their generous technical assistance with IMPRINT and beneficial IMPRINT training courses.

IV. Conclusion

4.1 Discussion

Implications for future systems. In the early stages of development, system architects have the powerful opportunity to determine how a new system will integrate with existing systems to accomplish a desired capability. If communication and team structure is not considered in this integration process, new systems which require real time distributed team communications will undoubtedly place higher demands on operators as missions become more complex and rely more on collaboration for their success. From a system of systems standpoint, these considerations were not made for the MQ-1/9, leading to immense variance in task loading during missions. Interviews showed that operators may swing from being bored to overwhelmed in a matter of minutes. Future system designs need to incorporate an understanding of the effective network size from the perspective of each operator in the system to optimize information flows. This research shows how this understanding can be incorporated into the design through modality allocation and team structure, which can each be dictated in early stages of development when design changes are the least costly. Multiple team structures should be considered and potentially simulated for various tasks in early development. Team structure could be designed to vary during the mission to accommodate dynamic shifts in workload.

Implications for future analyses. Previous works involving IMPRINT have not, to the author's knowledge, included a robust statistical analysis of workload data to compare multiple system configurations. This research uses vetted simulation study methods such as those outlined in Banks et al. (2010); Mitchell and Samms (2007) and Law (2006) to design experiments and determine the appropriate number

of replications needed to account for random variance. Multiple replications made possible the application of powerful statistical methods to determine quantifiable results in lieu of heuristic recommendations which are more widely used in workload prediction.

4.2 Future Work

MacMillan et al. (2004) were able to combine theoretical framework with empirical research to make conclusive recommendations about team structure. This work certainly contributes to a solid theoretical underpinning; future studies should incorporate human subjects experimentation and empirical study to test the results of this work. Multi-modal communication systems such as the one developed by the Air Force Research Lab (Finomore et al., 2009) could be used in conjunction with well developed RPA mission simulators to experimentally test the effectiveness of dynamic allocation of communication modalities to alleviate communication workload. Discrete event simulation is a good fit for modeling communication at the level presented in this research, though future analysts may consider agent based models to allow more granular and semantically oriented simulation. The results of the agent based model could then be worked onto the workload predictive capabilities of IMPRINT to make accurate inferences about communication priorities and semantic content. Should the opportunity arise, future researchers in this field should develop a large corpus of RPA operator communications. Having a corpus of both verbal and chat communications from an actual mission would help researchers understand the exact nature of communications in this arena in ways that interviews cannot. This corpus could be analyzed with latent semantic analyses (Dumais, 2004) to obtain measures such as the anticipation ratio and situation awareness measures discussed in MacMillan et al. (2004) to assess the effectiveness of team communication in real

missions. Analyzing communication data from real missions could be extremely difficult, so the author suggests attempts to study a representative RPA related exercise or war game to gather data. As it would be both unsafe and contemptible to perform experiments during real missions, simulators could be used to further validate team structure and system node changes and their effects on workload.

Remotely piloted systems have more communication channel options than systems where the pilot is in the aircraft, and this research implies that more diverse communication is not necessarily ideal in all conditions. Many operators prefer mIRC because of its effectiveness and persistence, but it is not a particularly rich media Robert and Dennis (2005). More connectedness between organizations certainly enable coordinations, but also increases communication overhead. Research to compare manned and unmanned systems and their respective team structures and communications architectures would be valuable.

IMPRINT allows the analyst the ability to set a workload threshold and simulate how an operator might manage the tasks to keep from being overwhelmed. This feature is particularly useful for determining which tasks are being delayed or dropped at certain times in the mission, and can be used to measure the number of delays for tasks of interest. This research shows that IMPRINT to create and measure multiple simultaneous metrics to show how changing the system affects different aspects of the operator's experience. The results show that workload, monitoring time and the number of delayed tasks are affected, but they do not provide a useful basis of comparison. Workload can be reduced by changing the number of communication nodes, but how much can it be reduced before boredom or change blindness begin to occur? Further work must be done to develop a theoretical optimum between task saturation, or 'red-line' (Grier et al., 2008) and boredom, or the 'blue-line' (De Waard, 1996).

Appendix A. MIC Questionnaire

General Questions

1. What are your major goals and functions as a MIC?
2. How long is a typical mission?
3. What are the major segments of your day?
4. Which channels do MICs use to communicate with parties within the GCS? How do they decide which channels to use at what times?
5. What is the process used to deal with large volumes of chat communication events? Are there scan patterns? What are the things you specifically look for?
6. How much chat information simply needs to be passed to another operator? How much is addressed particularly to the MIC? How much of it requires critical thinking, extra look-up tasks or problem solving?
7. Which parties have the highest priority during each mission segment?

Model Parameter Specifics

1. What are the major chat rooms for each segment of the mission?
2. How many parties are in each of the rooms?
3. In which rooms do you spend the most time reading and typing?
4. Which mission segments are the most heavy on chat? Are you able to read everything during that phase, or are you skimming/scanning the windows?
5. How long does it take to scan the chat windows unencumbered (in seconds)?

6. During each mission phase, how often (in seconds) do chat events come in from each of the major rooms?
7. If scanning, how often do you stop and read for comprehension?
8. On voice channels, how often do interruptions occur with each? To what are the interruptions attributed? How are the interruptions dealt with?
9. How often do chat windows fill up and result in excess scrolling for previous information? Is information sometimes missed completely?
10. When will you take information given on one channel and pass it through a different channel to another party? How often does this occur during a typical mission?
11. As a percentage of total chat, how much causes you to type?
12. As a percentage of total chat, how much causes you to speak on the radio?
13. As a percentage of total chat, how much causes you to speak on the intercom?

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704–0188

1. REPORT DATE *(DD–MM–YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From — To)*
22–03–2012	Master's Thesis	Aug 2010 — Mar 2012

4. TITLE AND SUBTITLE

Discrete Event Simulation of Distributed Team Communication Architecture

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GSE/ENV/12-M07

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/HP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT As the United States Department of Defense continues to increase the number of Remotely Piloted Aircraft (RPA) operations overseas, improved Human Systems Integration becomes increasingly important. RPA systems rely heavily on distributed team communications determined by systems architecture. Two studies examine the effects of systems architecture on operator workload of US Air Force MQ-1/9 operators. The first study ascertains the effects of communication modality changes on mental workload using the Improved Research Integration Pro (IMPRINT) software tool to estimate pilot workload. Allocation of communication between modalities minimizes workload. The second study uses IMPRINT to model Mission Intelligence Controllers (MICs) and the effect of the system architecture upon them. Four system configurations were simulated for four mission activity levels. Mental workload, monitoring time and the number of delayed tasks were estimated to determine the effect of changing system architecture parameters. Literature and MIC interviews provided parameters for the model. The analysis demonstrates that the proposed changes have significant effects which, in some conditions, bring the overall workload function toward a proposed theoretical optimum.

15. SUBJECT TERMS

Human Performance; Workload; IMPRINT; Communication: Systems Architecture; Discrete Event Simulation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Michael E. Miller, ENV
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